

Performance testing of a Fresnel/Stirling micro solar energy conversion system



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ABSTRACT

In this study, a beta-type Stirling engine was tested with concentrated solar radiation. The displacer cylinder of the engine was modified by integrating a concentrated solar radiation receiver. Basically, the receiver is a cavity drilled in a separate part mounted on top of the displacer cylinder by screws. Tests were conducted with three cavities made of aluminium, copper and stainless steel. The solar radiation was concentrated by a Fresnel lens with 1.4 m² capture area. Among the cavities, the highest performance was provided by aluminium cavity and followed by the stainless steel and copper cavities respectively. The maximum shaft power was observed as 64.4 W at systematic tests conducted with the aluminium cavity. The maximum shaft power corresponded to 218 rpm engine speed and 2.82 Nm torque. For this shaft power, the overall conversion efficiency of the system was estimated to be 5.64%. The maximum torque measured with aluminium cavity was 2.93 Nm corresponding to 177 rpm below which the engine stopped. The Fresnel-lens/Stirling-engine micro power plant established in this investigation was more efficient than the micro power plants presented in the literature.

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1. Introduction

Researches related to the conversion of solar energy into power were initiated in 1870 by John Ericsson, who established a micro solar energy conversion plant generating steam and producing power via a steam engine. The power of the prototype was reported as 373 W where the steam was produced directly in a collector [1]. It is also known that Ericsson built a solar engine working with air. The development of the petroleum industry and internal combustion engines decreased the interest in solar power after the end of nineteenth century. Until the petrol crisis in 1973, the interest in solar power was very low. After 1973, the petrol crisis stimulated investigation of solar energy, and a large number of research projects were initiated to develop solar energy technologies for electricity generation [2]. Investigations progressed in two different branches: photovoltaic and thermal power technologies [3]. Photovoltaic technology facilitates a direct conversion of sunlight into electricity via photovoltaic materials, which were discovered in 1839 by Edmund Becquerel [4,5]. In 1958, a second photovoltaic cell made of gallium arsenide was discovered with 11% conversion efficiency. In the 1960s, amorphous silicon cells were developed, which are more practical to use but less efficient than crystal photovoltaic cells. Photovoltaic cells

providing conversion efficiencies of about 30% were developed but have not been commercialized yet [6].

In solar thermal power technology, the conversion of the solar radiation into electricity is performed via a thermodynamic system and an electricity generator. So far, four different thermal power technologies have been developed and they are the parabolic trough, the power tower, the chimney, and the dish/engine [7].

In parabolic trough technology, the sunlight is concentrated onto a pipe receiver to heat up a heat transfer fluid. The heat transfer fluid conveys the heat to a heat exchanger where a high pressure vapour is generated. The generated vapour is fed to a steam turbine to generate power and electricity. The tracking mechanism of parabolic trough technology is one-dimensional and the concentration ratio is about 75 [3,8]. The parabolic trough technology is able to generate vapour at about 400 °C [1,9]. The first solar power plant with parabolic trough technology was established in California Mojave Desert in 1984, and it has been still generating electricity since then [10,11]. The total annual solar-to-electricity conversion efficiency of the parabolic trough system was reported as 15% [12].

The power tower technology is a point focusing system where a group of mirrors reflect the incident solar radiation onto a receiver placed on top of a tower. The mirrors aligned around the tower mostly have a spherical surface profile and they are called as a heliostat. In tower power technology, the concentration ratio of the solar radiation is between 500 and 1000. The receiver may have

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a temperature in excess of 1200 °C, and it is produced from ceramics capable of resisting high temperatures. The heat appearing in the receiver is used for generating high pressure steam. The steam obtained is expanded by a steam turbine coupled with an electricity generator. The power tower technology is also used for drinking water production, hydrogen production, and chemical reactions [13].

The solar chimney is a technology which converts solar radiation into electricity without concentrating the solar radiation. The chimney consists of a circular tower, a transparent roof, and an air stream turbine [14–17]. The air flow is induced by the buoyancy of warm air. The air is heated as a result of the greenhouse effect under the transparent roof, becoming lower in density, and thus a continuous air flow is induced. The air enters the system through the peripheral aperture around the roof and exits from the top of the tower. The turbine installed in the circular tower is run by the air stream, and the power obtained is converted into electricity by an electricity generator coupled to the turbine. The chimney built in Spain demonstrated the viability and reliability of the chimney concept, but the thermal conversion efficiency of the chimney was too low. To improve the thermal efficiency of the chimney technology, it was estimated that a tower having heights of hundreds of metres would be required [14].

The dish/engine system comprises a parabolic dish concentrator, a receiver, a heat engine such as a Stirling engine, and an electricity generator coupled to the engine. In these systems the dish concentrates and reflects the solar radiation into the receiver which is a cavity absorbing the radiation and transferring to the working fluid as heat. The engine converts the heat into the mechanical power and transmits to the electric generator [18].

In large dish/Stirling systems, having more than 100 m² collector area, constructed before 1990, kinematic and free piston Stirling engines were used. In most cases the engine and electric generator are constructed hermetically and charged with helium or hydrogen. The charging pressure of the working fluid to the engine was more than 100 bar. The expected performance appeared above 700 °C [18]. Because of very big installation expenditure and operating difficulties, these systems were abandoned [3]. After 1990, investigation of low cost and structurally simple solar energy systems became fashionable. In this content, the engines named as 'Low Temperature Difference' (LTD) attracted very much attention [19].

A parabolic concentrator used in a dish/Stirling solar system may provide a concentration ratio of more than 3000 [18]. For parabolic dishes made of back-silvered low-iron glasses, 70–80% reflection efficiencies were reported under 1000 W/m² solar radiation [20]. In dish/engine systems, the performance of the receiver is one of the most important factors determining the total efficiency of the system. Receivers used in solar energy application are designed at different shapes such as hemispherical, cylindrical, conical and so on [21]. A receiver may cause heat losses by radiation, convection and reflection [22]. For ordinary cavity receivers with no perfect isolation and absorptive surface, the efficiency is reported as lower than 40% [23]. In sophisticated receivers designed for dish/Stirling systems, the efficiency is reported as between 65% and 90% where the solar radiation is absorbed by the surface of the tubes, in which the working gas of the engine circulates, or by the surface of a sodium heat pipe [24]. Total conversion efficiencies exceeding 30% were reported for this system [18]. The total annual solar-to-electricity conversion efficiency of the dish/engine technology was reported as 18% [2].

In the current situation, the share of renewable energy technologies such as wind, solar, geothermal, and biomass in worldwide energy consumption is 2.1% [25]. For the current situation, the production of solar electricity is not attractive to private investors because it is not competitive with fossil fuel based electricity.

However, it is known that the combustion gases generated by internal combustion engines and thermal power plants have harmful effects on the health of living things and environment. Solar electricity is one of the plausible technologies to reduce the generation of combustion gases. In the near future, the electrical vehicles are expected to take place of the vehicles with petrol engines. These developments may increase the competitiveness of solar power via increasing the demand for electricity.

In this study a beta-type Stirling engine was tested with solar energy. The solar radiation was focused into a cavity situated on top of the displacer cylinder. To concentrate the solar radiation into the cavity, a Fresnel lens with 1.4 m² capture area was used. The influence of cavity materials on the performance of engine was studied by manufacturing and testing three cavities made of aluminium, copper and stainless steel. The highest performance was obtained with aluminium cavity.

2. Experimental facilities

In the experimental system, a non-regenerative, beta-type, Stirling engine was used by modifying its displacer cylinder. In this engine, heating and cooling of the working fluid is performed via the flow channel between the displacer and its cylinder. The channel also performs as a regenerator. Before modification of the displacer cylinder, the maximum power of the engine was measured as 253 W at 545 rpm engine speed, 4.5 bar helium charge pressure and 360 °C heater temperature [26]. The other technical specifications of the test engine are given in Table 1.

The modified displacer cylinder consists of two sections as seen in Fig. 1. The upper section works as a cavity and heater while the lower section works as a regenerator and cooler. The coupling of the sections was made with delicate flanges. The upper section (cavity and heater) was manufactured as a unique part and involves no resistance limiting the flow of heat from the cavity to the heater. Fig. 2 illustrates the dimensions of cavities made of copper and aluminium or stainless steel. The lower section of the displacer cylinder was manufactured from stainless steel. Fig. 3 illustrates the photographs of cavities made of aluminium, stainless steel and copper.

In order to prevent heat loss, the outer surface of the displacer cylinder was insulated from the surrounding air. A ceramic fibre blanket with thermal conductivity of $k = 0.08$ W/mK was used for isolation. The thickness of the ceramic blanket was 40 mm, and the free surface of the blanket was coated with aluminium foil. The heat transfer area at the working fluid side of the displacer cylinder was enlarged by growing span-wise slots 3 mm in depth and 2 mm in width [26–28].

The hot-end temperature of the displacer cylinder was measured via a thermocouple embedded into the cavity wall. The torque of the engine was measured by a Prony-type hand dynamometer.

Table 1
Technical specification of the test engine.

Parameters		Specification
Engine type		β
Power piston	Bore $\times$ stroke (mm)	70 $\times$ 60
	Swept volume (cc)	230
	Material	Aluminium
Displacer	Bore $\times$ stroke (mm)	65 $\times$ 79
	Swept volume (cc)	262
	Material	Stainless steel
Displacer cylinder	Material	Stainless steel
Lubricant filled in crankcase		SAE 20/50
Working fluid		Helium
Cooling system		Water cooled
Compression ratio		1.63

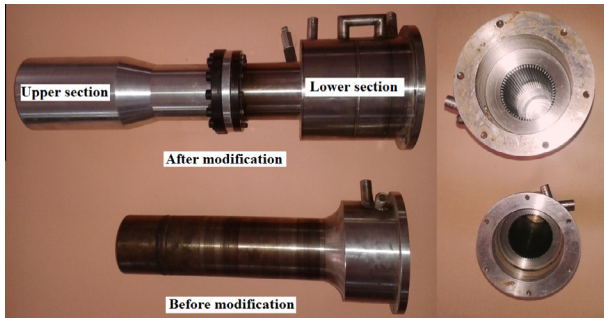


Fig. 1. The photograph of the displacer cylinder before and after modification.

momometer with a strain gauge load cell sensor. The accuracy of the dynamometer is 0.003 Nm. The engine speed was measured by a digital tachometer, ENDA ETS1410, with 1 r/min accuracy. Temperatures were measured with an ELIMKO-6000, multi-point electronic temperature indicator having 1 °C accuracy. The thermocouples used were NiCr–Ni type, which can measure up to 1200 °C. The pressure of the working fluid was measured by means of a Bourdon tube pressure gauge mounted onto the block of the engine. The solar radiation was measured with a Kipp–Zonen CMP 3 pyranometer.

Schematic illustration of the Fresnel-lens/Stirling-engine test system is shown in Fig. 4. The solar radiation was directly focused into the cavity. The engine and Fresnel lens were assembled on a platform made of wood and steel beams [29]. The platform had a two dimensional freedom of articulation to adjust to the sun. The adjustment was made by hand.

3. Results and discussion

Fig. 5 illustrates the speed–power and speed–torque curves obtained with the aluminium cavity at steady conditions. The

experiments were conducted at about 816 W/m² of solar radiation density. Since the capture area of the Fresnel lens was 1.4 m², the solar energy input of the engine was about 1142 W. During the experiments the bottom wall temperature of the aluminium cavity was about 425 °C. The maximum power was obtained as 64.4 W for 6 bar charge pressure. When the charge pressure was further increased, the torque and power became lower. It is known that the thermal efficiency of a cycle is related to the maximum and minimum temperatures of the cycle. The increase of working fluid mass limits the variation of the fluid temperature during the heating and cooling processes. This results in lower thermal efficiency and lower torque or power generation. The maximum power appears at 218 rpm while the maximum torque appears at about 177 rpm as 2.93 Nm. As it is seen from Fig. 4, the inclination of the torque with speed is almost linear. It does not pass through a maximum as the power does. Below 177 rpm, the vibration of the engine and fluctuation of the speed becomes larger, and the engine goes to stop.

After the tests of the aluminium cavity were finished, a stainless steel cavity having the same dimensions with aluminium cavity was manufactured and tested. Fig. 6 illustrates the speed–power and speed–torque curves obtained with the stainless steel cavity. The experiments were conducted at about 805 W/m² of solar radiation. The maximum power was obtained as 40 W at 5.4 bar charge pressure and 266 rpm engine speed. The maximum torque appeared as 1.67 Nm at 197 rpm engine speed. The bottom temperature of the cavity was measured as 205 °C, which was significantly lower than that of the aluminium cavity although the aluminium cavity and stainless cavity has the same dimensions. This indicates that the stainless steel cavity had more energy loss with back reflection and thermal radiation. Both the aluminium cavity and stainless steel cavity did not capture the all of the solar radiation concentrated by Fresnel lens. Some of the concentrated radiation dropped outside of the aperture of the cavity because the Fresnel lens underwent a deflection. The vibration of the whole system was also causing the radiation to drop outside the aperture.

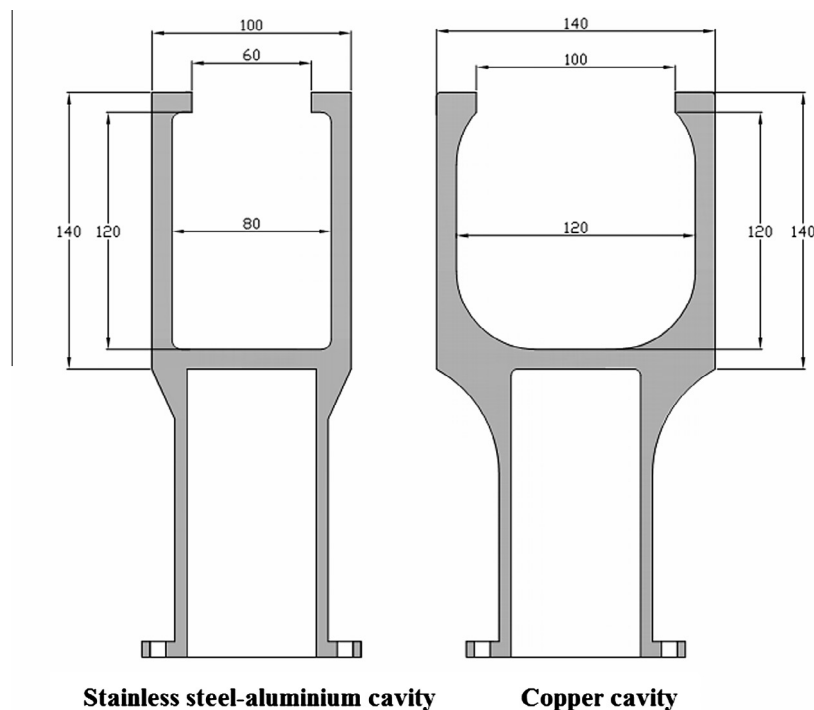


Fig. 2. The dimensions of the cavities made of copper and aluminium or stainless.



Fig. 3. The photographs of the cavities made of aluminium, stainless steel and copper.

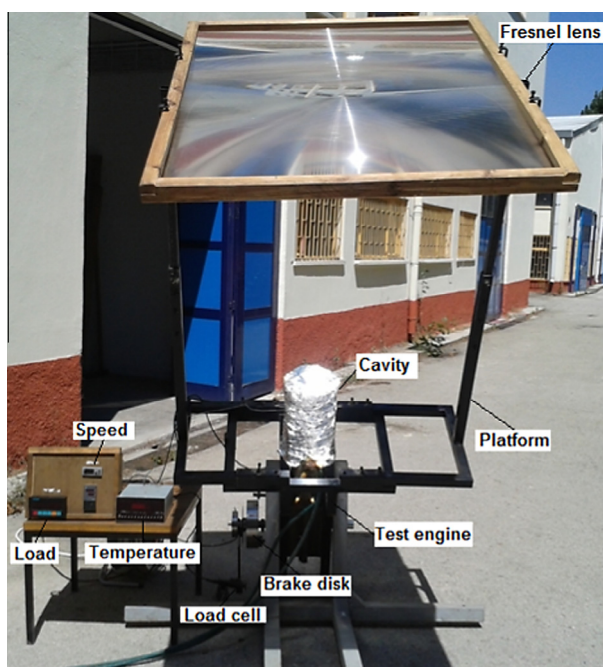


Fig. 4. The photograph of the test system.

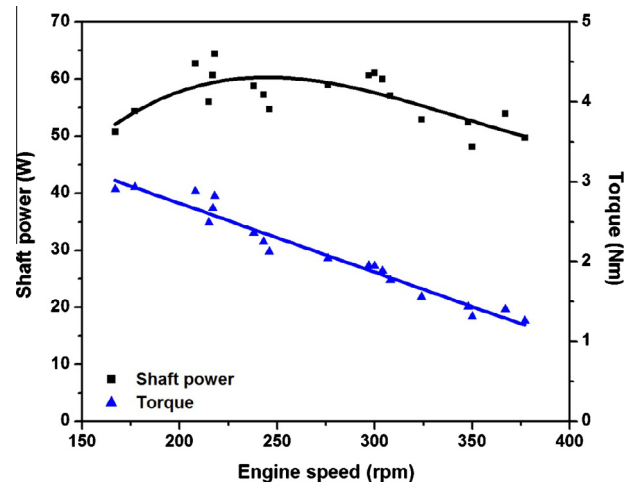


Fig. 5. Engine power and torque obtained with aluminium cavity at about 816 W/m² of solar radiation.

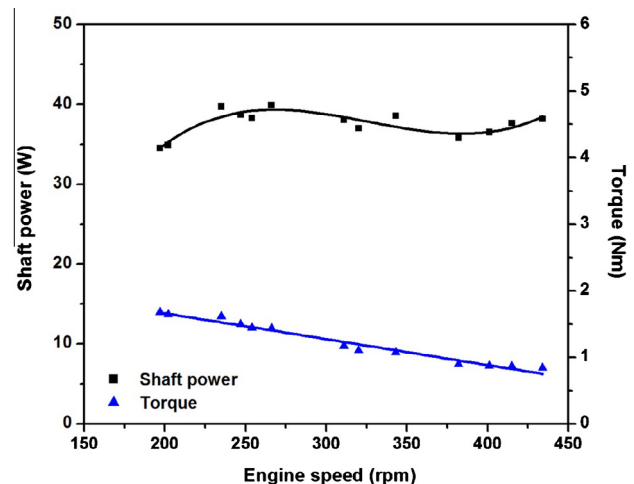


Fig. 6. Engine power and torque obtained with stainless steel cavity at about 805 W/m² of solar radiation.

Finally, a copper cavity was manufactured and tested. To allow the cavity to capture the whole of the radiation concentrated by the Fresnel lens, the inner and aperture diameters of the copper cavity were enlarged to 120 mm and 100 mm, respectively. Fig. 7 shows the speed–power and speed–torque curves obtained with the copper cavity. The experiments were conducted at about 820 W/m² of solar radiation. The bottom temperature of the cavity was measured as 185 °C, which was rather lower than that of the stainless steel cavity. The maximum power obtained at 4.7 bar charge pressure was about 22 W. The maximum power appeared at about 291 rpm while the maximum torque appeared at about 156 rpm and it was 1.09 Nm.

It is notable that the torque curves of the aluminium, stainless steel and copper cavities are different from each other as trend. The resisting characteristic of the engine (increase of the torque while speed decreasing) with the aluminium cavity is two times with the stainless steel and four times with the copper cavity. On the other hand the melting temperature of the aluminium cavity presents a disadvantage. During the experiment, it was observed that the concentrated solar radiation begins melting if it is focused on a small enough area on the aluminium cavity.

The efficiency of the cavity may be described as:

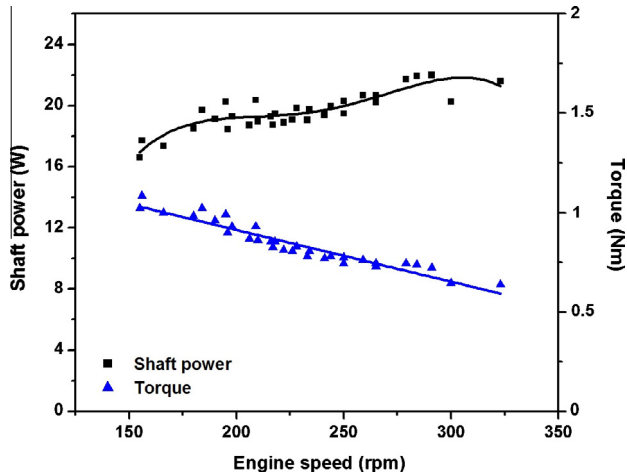


Fig. 7. Engine power and torque obtained with copper cavity at about 820 W/m² of solar radiation.

$$\eta_c = \frac{\text{Heat generated in the cavity}}{\text{Concentrated solar radiation}} \quad (1)$$

In the above equation, the denominator is the rate at which radiation is converted to heat. Its determination by experimental measurement is almost impossible. Therefore, there is a need for an indirect determination procedure. The overall efficiency of the plant and the reflection efficiency of the Fresnel lens allow the solar-to-heat conversion rate to be predicted indirectly. In this investigation, the optical performance of the Fresnel lenses was predicted as about 65–70% via an experiment. In this experiment, the radiation reflected by the lenses was used to heat a certain mass of water. The reflected radiation (heat) was calculated from the temperature increase of the water. The reflection efficiency of the lens was estimated from the ratio of heat to radiation, where the radiation was measured with a pyranometer. The efficiency of Fresnel lens (η_f) was estimated to be 65%.

The overall thermal efficiency of the plant may be expressed as:

$$\eta_t = \frac{\text{Engine shaft power}}{\text{Incident radiation onto the Fresnel lens}} \quad (2)$$

In the last equation, substituting the maximum shaft power presented above and the corresponding solar radiation, the overall efficiency of the plant is determined as:

$$\eta_t = \frac{64.4}{1142} = 0.0564.$$

It is also necessary to know the thermodynamic efficiency of the engine (η_e). By introducing the experimental conditions into the nodal analysis presented in a previous publication of the research group [30], the thermal efficiency of the engine was estimated to be about $\eta_e = 19.2\%$ where the heater temperature was taken to be 425 °C. The thermal efficiencies of the engine with the stainless steel and copper cavities were estimated to be 13.34% and 8.11%, respectively by introducing 205 °C and 185 °C heater temperature.

The overall total efficiency of the plant may also be stated as:

$$\eta_t = \eta_c \eta_e \eta_f. \quad (3)$$

From the last equation, the efficiency of aluminium cavity is calculated as

$$\eta_c = \frac{\eta_t}{\eta_e \eta_f} = \frac{0.0564}{0.192 \times 0.65} = 0.4519$$

Similarly, the efficiencies of the stainless steel and copper cavities were estimated to be $\eta_c = 40.82\%$ and $\eta_c = 36.42\%$. These results indicated that the cavity efficiency is one of the key issues in

this type of solar energy conversion plant. The cavity efficiency is inadequate for several reasons, and it is estimated that the major reasons are the focusing error, back reflection of some solar radiation, thermal losses, and material properties.

The overall thermal efficiencies of the plant obtained with aluminium, stainless steel, and copper cavities are illustrated in Fig. 8. The maximum efficiencies were 5.64%, 3.54%, and 1.92% for aluminium, stainless steel, and copper cavities, respectively. In the literature published after the year 2000, there are only two investigations on the micro solar energy power plants based on Stirling engines. One of them was conducted by Kongtragool and Wongwiswes where a parabolic-dish concentrator with 3.14 m² capture area and a LTD Stirling engine were used. The maximum overall efficiency of this plant was reported as 1% [31]. The other study was conducted by Tavakolpour et al. where a flat-plate collector with 0.5 m² capture area and a gamma type LTD Stirling engine were used. The maximum overall efficiency of this plant was reported as 0.26% [32]. The most appropriate cavity material seems to be aluminium. However, its melting temperature imposes a disadvantage. Although the tests conducted with three cavities were carried out under almost the same radiation density, the performance of the engine exhibited very big variations. Obviously, some of these variations are caused by the varying cavity efficiencies but, the whole variation may not be attributed to the cavity efficiencies.

Theoretical analysis indicates that in an engine with regenerative displacer, a wall temperature distribution of linearly varying in the spanwise direction of displacer cylinder, from T_h to T_c , provides a higher performance [33]. The thermal conductivity of the copper is about 400 W/mK. Such a large thermal conductivity does not enable a linearly varying temperature in the spanwise direction of displacer cylinder. The temperature of the upper section (copper cavity) is relatively more uniform and lower (about 185 °C). The heat loss to the cooling water through the displacer cylinder is also relatively larger. As the result of these, the performance of the plant becomes lowest with copper cavity.

The thermal conductivity of the stainless steel is less than 20 W/mK. Such a low thermal conductivity may prevent the flow of heat in the spanwise direction through the displacer cylinder. This may reduce the system performance a bit. But, the bottom temperature of the stainless-steel cavity was measured as 205 °C which indicates that the main disadvantage of the stainless-steel cavity is its lower absorptivity.

A cavity material with a thermal conductivity of about 100 W/mK may be useful to improve the performance of the engine. The cavity material should also have a high absorptivity and a

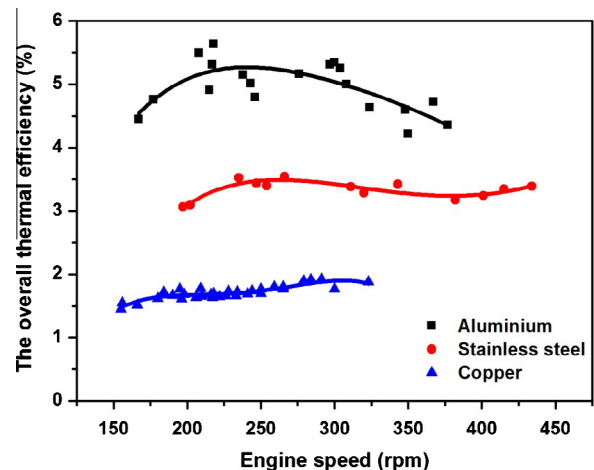


Fig. 8. The overall thermal efficiency of the plant obtained with aluminium, stainless steel, and copper cavities.

low emissivity. The thermal conductivity of the pure Nickel is 90 W/mK which is in the desired range. The absorptivity of bright nickel with blackened surface is about 96% while its emissivity is less than 0.1. The Nickel seems to be more appropriate for cavity material which is already used in solar energy technology as a surface coating material [34]. For the development of a cavity having an adequate efficiency, a comprehensive study including experimental and theoretical procedures seems to be necessary.

4. Conclusion

Solar radiation was focused in a cavity using a Fresnel lens with a capture area of 1.4 m². Three different cavities made of aluminium, stainless steel, and copper were manufactured and tested under solar radiation. The maximum performance was obtained with an aluminium cavity as 64.4 W power and 5.64% overall total efficiency. The copper cavity provided the lowest performance as 22 W power and 1.92% overall total efficiency. The efficiencies of the cavities made of copper, aluminium, and stainless steel were estimated to be 45.19%, 40.82%, and 36.42%, respectively. The total efficiency was found to be lower than expected. It is estimated that the focusing error, back reflection of some solar radiation, thermal losses, and material properties were the major reasons for the inadequate performance.

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